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Speciation of Arsenic and Nickel in Sediments of Moira Lake

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The National Uranium Tailings Program
Canada Centre for Mineral and Energy Technology
Energy, Mines and Resources Canada
555 Booth Street
Ottawa, Ontario
K1A 0G1

by

R.J. Cornett and L. Chant
Atomic Energy of Canada Limited
Chalk River Nuclear Laboratories
Chalk River, Ontario
K0J 1J0

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SUMMARY

Nickel and arsenic have flowed into Moira Lake since the start of milling operations in the lake's drainage basin more than 100 years ago. This study has determined the distribution of Ni and As in the waters of Moira Lake and in a series of sediment cores collected from the lake bottom. Additional measurements of Ni and As chemical fractionation and concentrations in the porewaters of the lake sediments were made to test for the potential of As and Ni remobilization from the lake sediments back to the overlying water.

Most of the As and Ni measured in the surface waters of Moira Lake was found to be in the dissolved fraction. This observation and the lack of a correlation between the areal distribution of As and Ni in the lake sediments and the location of the source suggest that the input of particulate As and Ni from the tailings is small.

The distribution of As within the sediment cores and around the lake bottom was strongly correlated with the distribution of Ni. Almost all of the As and Ni present in Moira Lake was found in the sediments. Concentrations in the overlying waters were 10^4 to 10^5 times lower than those measured in the bottom sediments.

Both As and Ni appear to be mobile within the sediment column. This conclusion is based upon the observations that: a) there are significant gradients in the concentrations of both elements in the sediment porewaters, b) both elements are found in chemical fractions that could be decomposed by natural diagenesis or by anthropogenic alterations to the lake's chemistry, and c) the distribution of Ni and As in different chemical extracts changes significantly between the mud-water interface and the deepest sections of the cores.

The distribution and fractionation of Ni and As in the Moira Lake system was very similar to that reported in other systems. Since the source of the Ni and the As in Moira Lake is different than the sources in other systems (e.g. atmospheric inputs, other types of tailings, natural inputs, etc) this supports the hypothesis that generalizations about the behaviour of elements in surface waters can be made that are independent of the individual source.

The distribution of Ni and As in the Moira Lake system provides a strong empirical data base with which to predict the behaviour of Ni and As in other systems and to calibrate more complex geochemical models.

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1. INTRODUCTION

1.1 RATIONALE

The National Uranium Tailings Program is charged with assessing potential environmental hazards present in uranium mill wastes or tailings. Of prime concern to environmental managers are the mobile radionuclides and toxic heavy metals present in the tailings (Snodgrass et al. 1983). These elements may be leached from the tailings and migrate down a hydrologic gradient to contaminate groundwaters and surface waters. Two elements of potential concern are Ni and As (Ferguson and Gavis 1972). Since the complex uranium ores found in Saskatchewan contain significant quantities of these two elements, the tailings from mining operations will also contain large quantities of these contaminants. Information on the geochemistry of these elements is required to predict their future behaviour in surface waters located downstream from the tailings. This study examined the geochemistry of Ni and As in Moira Lake water and sediments. This lake provided a unique opportunity to examine the distribution and chemical partitioning of these two contaminants in freshwaters after they were leached from tailings and refinery wastes into the Moira River, which is the principal inflow into Moira Lake.

1.2 STUDY OBJECTIVES

Milling operations located on the Moira River have discharged Ni and As into the river over a period of greater than 100 years (Bowles 1982). Previous studies have shown that the water and sediments of Moira Lake contain elevated concentrations of several metals (Mudroch and Capobianco 1980; Evans et al. 1986; McCulloch 1984). The specific objectives of this study were to:

(a) Measure the lakewater concentrations of Ni and As in the particulate and dissolved fractions.

(b) Determine the areal and historical distributions of Ni and As in the lake sediments.

(c) Construct a mass balance for the distribution of the elements in the lakewater and sediments.

(d) Measure the distribution of Ni and As in the porewaters and solid sediment matrix and determine the fraction of each element extracted sequentially using the extraction procedures of Tessier et al. (1979).

(e) Use this data to test for the possibility of remobilization of As and Ni from the lake sediments to the overlying water.

1.3 BACKGROUND

Following the discovery of gold about 1860 in the Moira River Basin, a series of mines were operated near the town of Deloro, a small village on the Moira River approximately 10 km upstream from Moira Lake (Fig. 1). By 1900 gold was mined, milled and smelted at Deloro and the As wastes in the ore found a market as pesticides. Throughout the 1900's silver and cobalt ores from Cobalt, Ontario, African ores, and Moroccan ores were all processed at the smelting

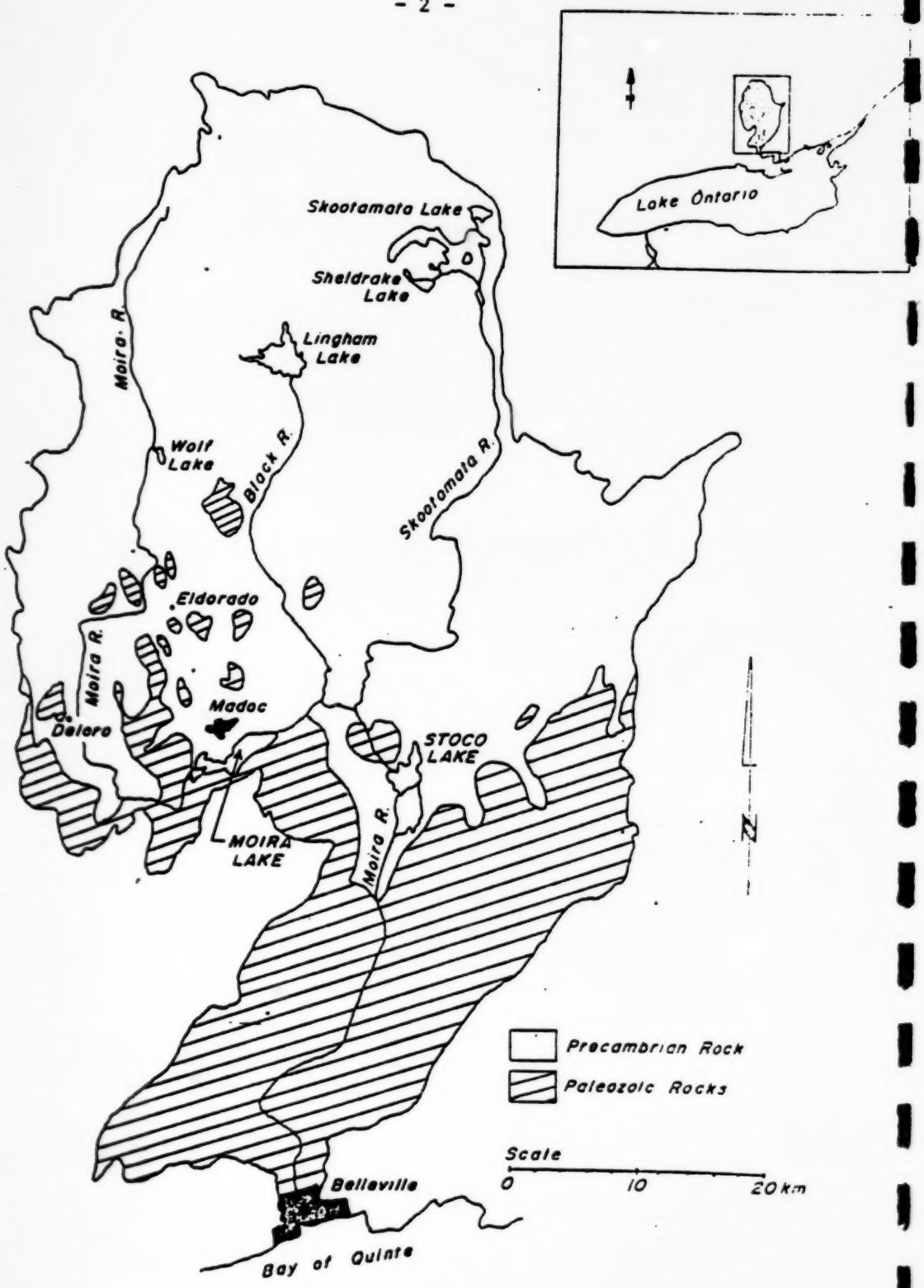

Figure 1 - MOIRA RIVER WATERSHED
(Source : Mudroch & Capobianco 1980)

and refining operations. At least some of these ores contained Ni and As (Diamond 1986, pers. comm.). A combination of events resulted in the cessation of all operations at Deloro in 1961.

The complex history of milling operations in the Moira Lake is only known qualitatively. There are significant quantities of wastes located in tailings sites along the Moira River (Reid et al. 1980). These contain quantities of calcium arsenite, arsenic trioxide, ferric hydroxide tailings, and other miscellaneous tailings and chemical wastes. Although groundwater leachate and runoff from the tailings site are treated by a water purification plant, As and Ni still leach into the Moira River (McCulloch 1984). Arsenic is the only metal monitored in the Moira River near Deloro. Records suggest that the amount of As entering the lake has decreased since refining operations ceased in 1961 (Ontario Ministry of the Environment, unpublished data). The amounts of Ni and As entering the Moira River system in earlier years are unknown. However measurements of the concentrations of nickel, arsenic, cobalt, copper, lead, zinc, chromium, mercury and silver in the lake sediments show significant enrichments of As, Ni and Co (Mudroch and Capobianco 1980). Elevated levels of several other metals were also observed in the river sediments downstream from Deloro. The chronology of contaminants in Moira Lake sediments (determined by Pb-210 and stable Pb dating) suggests that contaminants have leached from the tailings into the river system throughout the past century (Evans and Cornett, unpublished data).

2. METHODS

2.1 STUDY AREA

Moira Lake lies approximately half-way in the Moira River watershed (Fig. 1). Bedrock geology to the north of the lake consists of Precambrian rock of plutonic, meta-sedimentary and meta-volcanic origin (Sibul et al. 1974). The bedrock is exposed in the northern part of the basin but overlain by up to 83 m of Ordovician limestone in the southern areas. The basement rock is covered with an overburden of sand and gravel, glacial till and lacustrine sand, silt and clay deposits. The fine grain lacustrine deposits are more predominant in the southern sections of the basin (Sibul et al. 1974).

The characteristics of Moira Lake are summarized in Table 1. Moira Lake is a larger (827 ha) lake formed by a widening in the Moira River (Mudroch and Capobianco 1980). It is a shallow system (mean depth 4.4 m) divided by a constriction into 2 separate basins (Fig. 2). The major inflow containing the Ni and As enters the smaller, shallow, northern basin at the head of the lake. This inflow, the Moira River, supplies the vast majority of the water to the lake and flushes the lake quite rapidly (water residence time 0.35 yr) (Water Survey of Canada, 1977). There is a significant input of anthropogenic nitrogen and phosphorus into the lake. As a result, Moira Lake is more eutrophic than most lakes in the area. The lake water's pH is approximately 8.0. Total dissolved solids, alkalinity and hardness values > 125 ppm suggest that the lake is buffered by the carbonates in the basement rock and in the overburden material (Table 1).

2.2 SAMPLING METHODS

Water samples and cores of lake bottom sediment were collected on two different occasions. Fifteen core samples were collected from Moira Lake between October 17 and November 8, 1983 by McCulloch 1984. Eight additional cores were collected for this study on November 14, 1985. The location of the sampling sites used in both years is shown in Figure 2. All cores were collected with a K-B gravity corer using 6.35 cm (1983) or 7.0 cm (1985) inner diameter lucite core tubes. Cores collected in 1983 were immediately sectioned at 2-cm intervals using an extruder and a plastic collar. Then the sections were placed in polyethylene jars and frozen within 48 hr. Samples collected in 1985 were kept intact until they were returned to Chalk River Laboratories. At the laboratory the water overlying the cores was removed and the cores were sectioned in 1 cm or 2 cm sections under a nitrogen atmosphere. Then all samples were frozen in containers purged with nitrogen gas. These precautions were taken to prevent oxidation of the samples and to maintain the in situ redox conditions. As an additional precaution the outer ring of core material (0.5 cm) was discarded in each sample. During subsequent processing of these cores, a nitrogen atmosphere was always maintained over the samples.

2.3 EXTRACTION OF ARSENIC AND NICKEL

The sediment cores referred to earlier were analyzed by two different procedures. The total amount of As and Ni in the sediment samples were determined or the quantities of As and Ni contained in each fraction extracted sequentially using the procedure of Tessier et al. (1979) were measured. Total Ni and As were measured on 6 cores collected by McCulloch (1984). Prior to

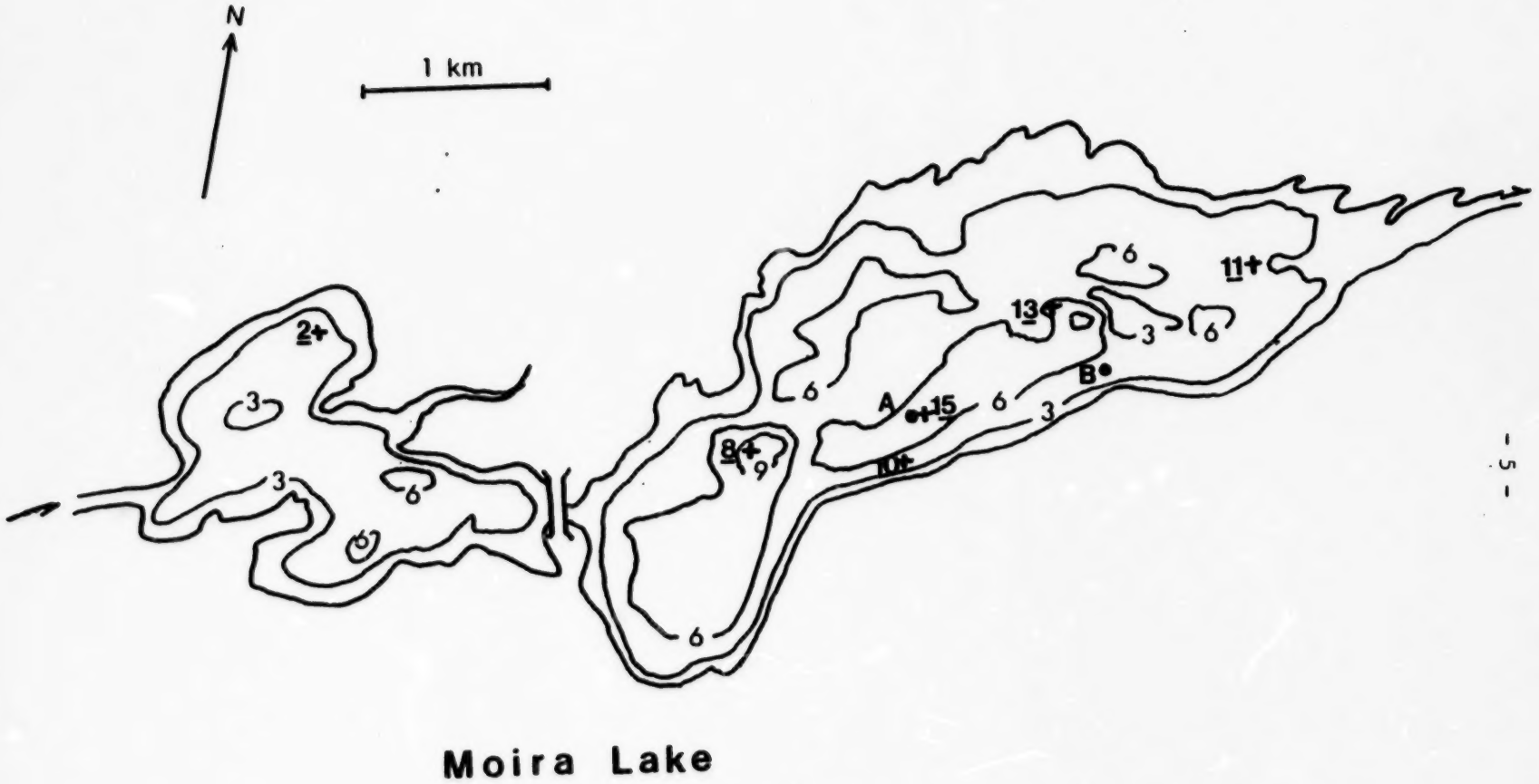

FIGURE 2. Morphometry of the lake and location of sediment cores collected in 1983 (+) and 1985 (·).

TABLE 1

CHARACTERISTICS OF MOIRA LAKE

Latitude Longitude	44° 30' 77° 27'	
Surface Area	827 ha	MNR[1] (1969)
Maximum Depth	11 m	"
Mean Depth	4.4 m	"
Volume	$36 \cdot 10^6 m^3$	"
Water Residence Time	0.34 yr	WSC[2] (1977)
pH	8.0	Mudroch and Capobianco (1980)
TDS[3]	207 ppm	Owen and Galloway (1969)
Hardness	152 ppm	"
Alkalinity	136 ppm	"
Conductivity	220 $\mu s\ cm^{-1}$	this study

1 Ministry of Natural Resources for Ontario

2 Water Survey of Canada, Fisheries and Environment Canada

3 Total dissolved solids

analysis the sediments were dried overnight at 70°C and then ground to a fine powder. McCulloch (1984) extracted the Ni from the bulk sediment by acid digestion using a 2:1 mixture of HCL:HNO_3 at 80°C until dryness (~ 3 hr). The resulting slurry was filtered and the filtrate saved for analysis. In this study, As was extracted from 0.5 gm sub-samples of the same cores by acid digestion using concentrated HNO_3 and H_2O_2. The extract was diluted with 2.0 N HNO_3 prior to spectrophotometric analysis.

Samples from two sediment cores (Sites A and B in Figure 2) were analyzed using the sequential extraction procedure of Tessier et al. (1979). Each sample was centrifuged under nitrogen to separate the interstitial water from the solid matrix. The interstitial water was poured off into acid washed vials and the solid matrix was sub-sampled for chemical partitioning. The sequential extraction procedure separated metals into the following fractions based upon their solubility:

a) easily exchangeable (extractable into 1 M $MgCl_2$, pH 7.0),

b) bound to carbonates (extractable in 1 M NaOAc buffer at pH 5.0),

c) bound to Fe or Mn oxides (extractable into 0.04 M NH_2OH-HCL in 25% HOAc),

d) bound to organic matter (extractable into 30% H_2O_2 adjusted to pH 2 with HNO_3), and

e) the remaining residual fraction (extractable in 2 digestions of concentrated HNO_3).

The detailed procedure of Tessier et al. (1979) was modified in several ways so that:

a) wet, bulk samples were analyzed rather than dried, ground material,

b) the in situ redox conditions were maintained under a nitrogen atmosphere and the first three extractions were performed under this atmosphere, and

c) concentrated HNO_3 was used to extract the As and Ni in the residual material.

2.4 ANALYSIS OF NICKEL AND ARSENIC CONCENTRATIONS

Nickel concentrations reported in this report were analyzed by two methods. Samples analyzed by McCulloch (1984) were measured by direct aspiration of the leachate into a Varian-AA-375 atomic absorption spectrophotometer equipped with a deuterium background corrector. During this study concentrations of Ni were measured in samples of lakewater, particulate material, porewater, and the leachates described in section 2.3. The absorbance of Ni at 232 nm in the solution was determined using a Hitachi-170-70 graphite furnace atomic absorption spectrophotometer. To minimize the influence of the sample matrix, all analyses used a Zeeman background correction (Vollkopf et al. 1983). This method was chosen for our analyses because it has a significantly lower detection limit and because it eliminated much of the background interference produced by variable matrix effects.

Arsenic concentrations in the leachate solutions were measured using an ILI model 353 atomic absorption spectrophotometer. Arsenic in the solutions was reduced by the addition of sodium borohydride. The arsene gas formed was then carried with argon through a heated, windowless quartz cell where the As was atomized. The absorption of the sample at 193.7 nm was recorded (Peacock and Sing 1981). The absorbance of samples, standards, and blanks treated in an identical manner was determined.

2.5 QUALITY ASSURANCE

Three steps were taken to insure the accuracy and precision of the Ni and As concentration measurements made during this study.

First, the concentrations of As and Ni in all reagents and in the total process blank were determined. Arsenic and Ni concentrations in the double distilled, deionized water were below the lower limit of detection. In all the reagents used, there was detectable contamination of As only in the H_2O_2 solutions. Small amounts of nickel contamination were found in HNO_3 and in several extracts used in the sequential extraction procedure (see Section 2.3). All analyses were corrected for these reagent blanks.

The significance of matrix interferences in the Ni and As determinations was evaluated for all solutions using the standard addition technique. Matrix suppression was observed in all samples prepared by concentrated acidic digestion techniques. As a result standard addition was used for both Ni and As analyses in these extracts. Matrix effects were not found in the porewater or in other solution extracts. However the standard addition technique was used as a precaution to measure the Ni and As concentrations in water samples. This precaution was used because the concentrations of both elements were quite low.

The accuracy and precision of the analytical techniques used in this study were evaluated by analyzing internationally accepted certified reference standards. We analyzed IAEA-W-4, a simulated freshwater standard and IAEA-SL-1, a freshwater lake sediment sample. The means of triplicate analyses of these samples agreed well with the certified values (Table 2). Comparing the expected and measured values using t-tests showed that none of the deviations from the certified values were statistically significant. The coefficient of variation for the triplicate analyses ranged from ~ 4 to 17%. As noted in other studies (e.g. Evans et al. 1984) the variability in analyzing sediment samples was higher than that for water samples analyzed for the same element.

2.6 OTHER ANALYSES

To characterize the geochemical environment of the sediment cores collected for chemical speciation analyses, several additional chemical determinations were made. These determinations have aided in the geochemical interpretation of our results. The measures will also provide information for the As and Ni geochemical modeling validation program of the NUTP (Snodgrass, pers. comm.).

The water content of each slice of the cores was calculated by the change in weight between the wet material and the sample dried to a constant mass. The organic content of the dry matrix was determined by loss on

TABLE 2

ANALYSIS OF STANDARD REFERENCE MATERIALS+

Element	Matrix	Standard	Expected Value	Our Analysis
As	freshwater	IAEA/W-4	25	24.5±1.1
Ni	freshwater	IAEA/W-4	2.5*	2.3±0.3
As	sediment extract	IAEA/SL-1	27.5±2.9†	23.3±3.9
Ni	sediment extract	IAEA/SL-1	44.9±8.0	46.9±6.0

+ all values in ppm

* simulated freshwater prepared with known concentrations of As and Ni

† results of interlaboratory comparisons

ignition. Samples were heated in a muffle furnace at 475°C for 16 hours and the change in sample mass was determined. The pH and Eh of the porewaters were measured in a closed system using Ross and Orion electrodes, respectively coupled to an Orion analyzer. The concentration of free sulphide in the porewaters was also measured by direct ion-selective electrode potentiometry in unconcentrated porewater samples (Vivit et al. 1984). The samples were adjusted to contain 0.2 M NaOH - 0.1 M Ascorbic Acid - 0.02 M EDTA. Most of the detected sulphide appears to arise from "hydrolysis" of various organo-sulfur compounds (under the alkaline and reducing conditions), or hydrolysis of metal-sulphide complexes (in the presence of excess EDTA) (Gulens pers. comm.). Results in the range 0.3 - 2 $\mu g \cdot L^{-1}$ are probably accurate to about a factor of 2, but nonetheless do indicate a real presence of S^{2-}. During all porewater measurements, the redox conditions of the original sample were maintained by manipulating the samples under a nitrogen atmosphere. Concentrations of anions in the porewaters were determined by eluent suppressed ion chromatography (Jay and Judd, 1985) using a Dionex model 10 system. The concentration of major cations in the porewater and in the solid matrix was analyzed by inductively coupled plasma emission spectroscopy. All methods were tested using standard reference materials.

3.0 RESULTS

3.1 GEOCHEMISTRY OF MOIRA LAKE SEDIMENTS

The water content was measured in all cores. Figure 3 shows that cores A and B, collected for this study, have very high porosity. Water contents in the surficial slices are greater than 95%. A decrease in water content with depth is typical of shield lake sediments. It is caused by compaction of the soft overlying gyttja. Although the changes in water content are slight between most sections, a change from 95% to 90% is equivalent to a doubling in the amount of solid matrix in the section. Core B also shows a significantly lower water content in the basal sections. In this core, gyttja overlays a sand gravel basement material of lower porosity. The sediment matrix is composed of organic and inorganic material. The organic matter content of the sediments ranged from 30 to 45% throughout Core A; similar values were seen in the upper portions of Core B. However the sand and gravel at the base of Core B had a much lower loss on ignition (Fig. 3).

The pH of Moira Lake sediments was very similar to that measured in the water (Table 1). pH values of 8.0 - 9.0 were measured from the top to the bottom of the cores over a depth interval of ≈ 25 cm (Fig. 4, Appendix 6). The alkaline pH of the water and sediments results from carbonate inputs from the Trenton Limestone bedrock which underlies parts of the lake and its drainage basin (Fig. 1). Unlike the constant pH observed in the cores, Eh values changed from +165 mv to 0 mv from the mud-water interface to the bottom of the core. The decrease in Eh values with depth in the cores is consistent with the sulphide chemistry measured in the porewaters. Sulphide concentrations increase from ≈ 5 to 80 ppb deeper in Core A (Fig. 4). Concentrations of sulphide were much lower in Core B (Appendix 6). This reflects both lower organic matter and higher Eh values measured in this core. Variability in the sulphide measurements reflects the difficulty in maintaining strict anoxic conditions throughout the porewater extractions and measurements. However the data clearly show that the sulphide concentrations are very low.

Other anions are much more important in the porewater than sulphide. The major inorganic anions in porewater from Cores A and B were $SO_4^=$, NO_3^-, F^-, and Cl^-. Profiles of fluoride and chloride display no significant trends with depth (Fig. 5). Both sulphate and nitrate are very active in the geochemical redox cycles in lake sediments. The concentration of both anions decreases significantly in more reducing sediments (Fig. 6). In Core A, sulphate and nitrate concentrations decrease throughout the core profile. Core B shows only a slight decrease in sulphate concentrations and the concentration of nitrate changes very little with depth. The difference between the two cores appears to result from a difference in the matrix material. Core B contains a predominantly inorganic sandy basement material while Core A is composed exclusively of gyttja.

The difference in the composition of the gyttja and sandy basement material can also be seen when concentrations of major cations are compared (Appendix 5). Concentrations of Ca are lower and Al concentrations in the inorganic sands are elevated over those in the top of Core B or in the gyttja of Core A. Concentrations of Mg, Fe and Ba did not change significantly over the length of the core. The measures are more erratic in Core B. Visually, this core also appeared to have the most heterogeneous matrix. The composition of

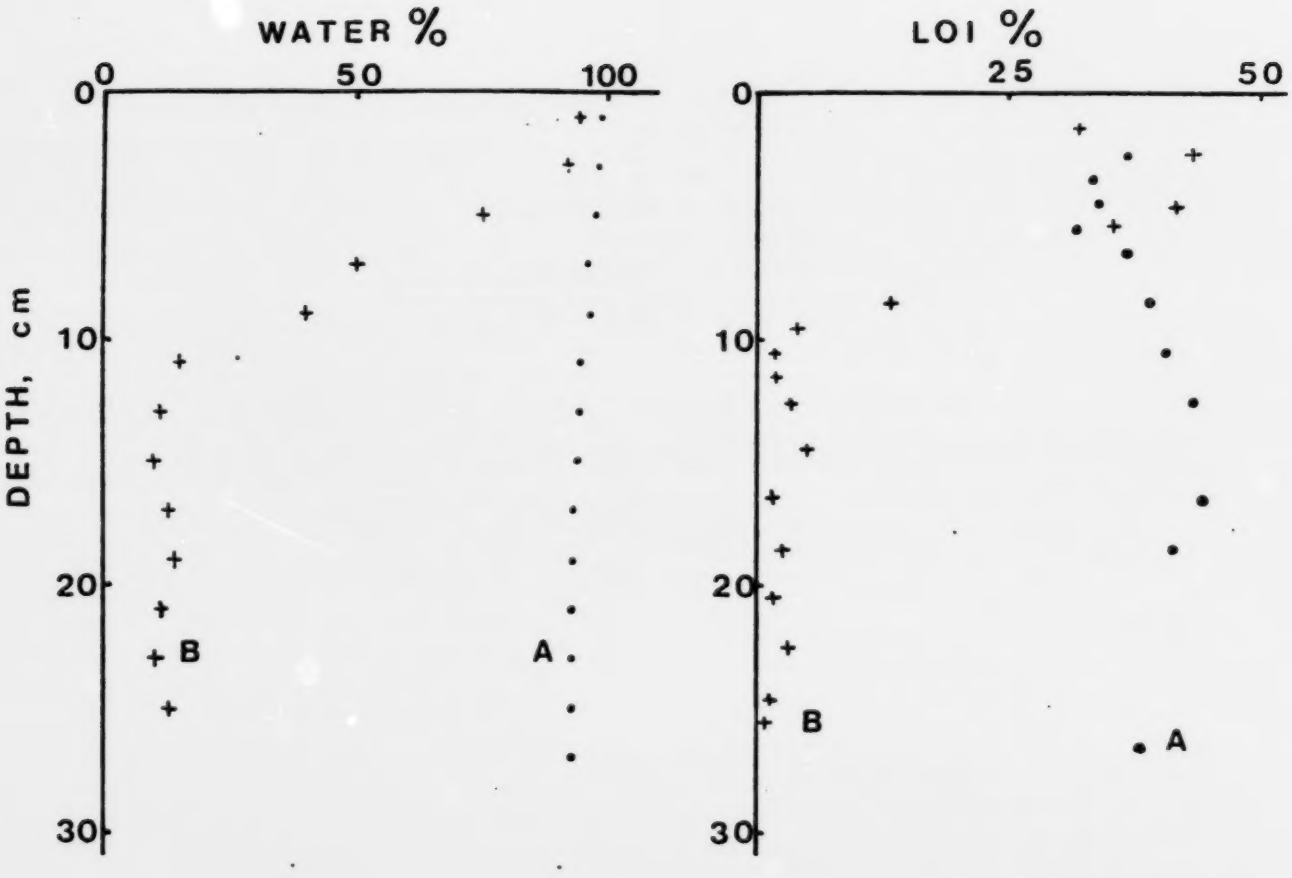

FIGURE 3 Water content and organic content (loss on ignition) of two cores of Moira Lake sediments.

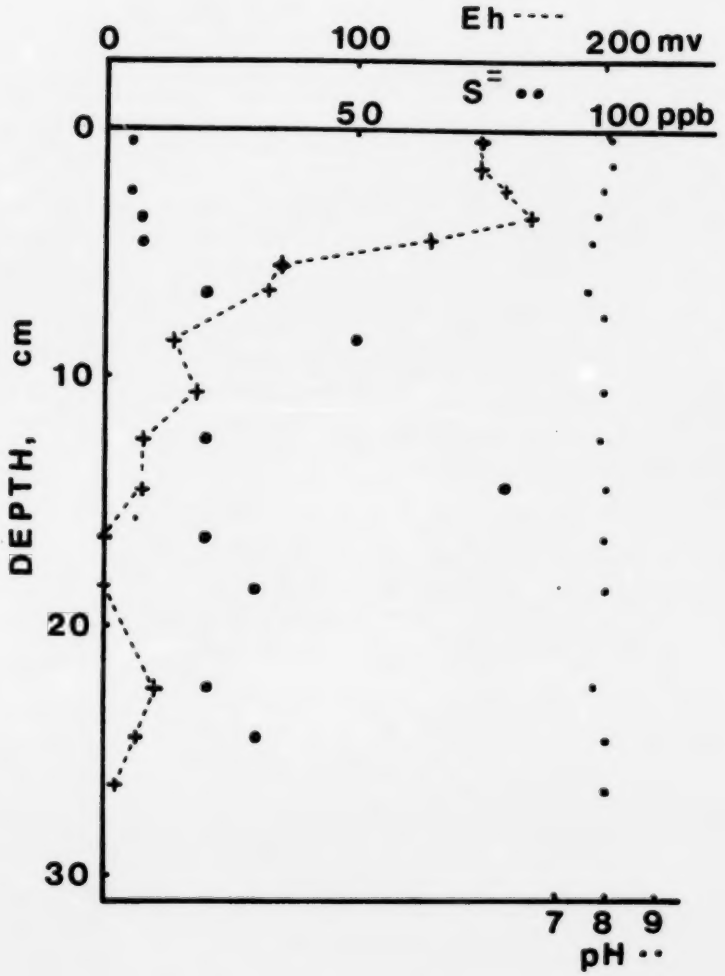

FIGURE 4 pH, Eh and sulphide concentrations in the porewater of Core A.

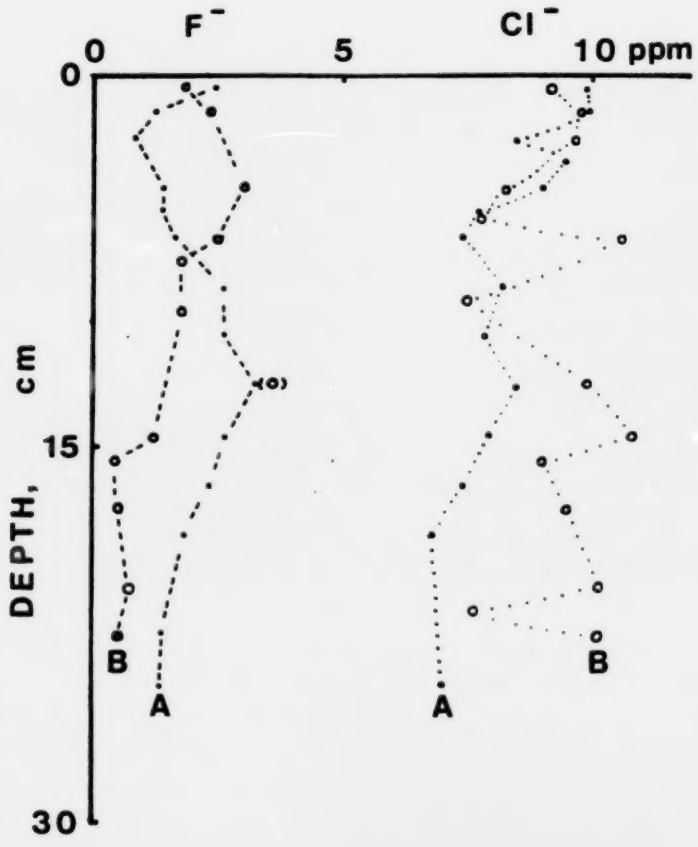

FIGURE 5 Vertical profiles of fluoride and chloride in the porewater of two cores.

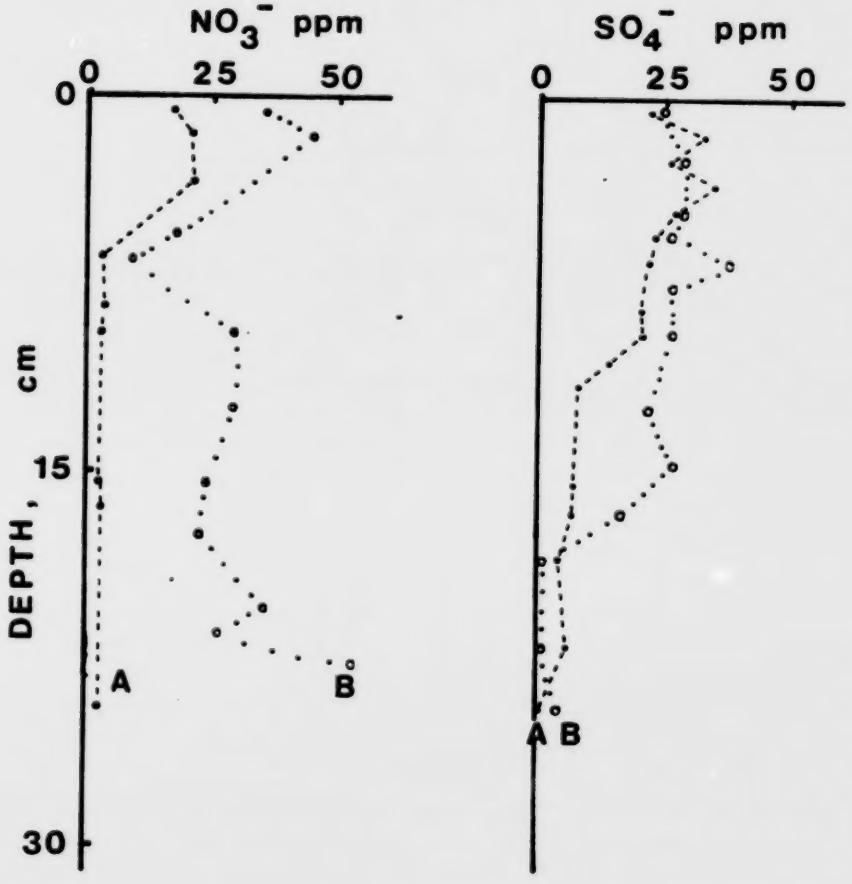

FIGURE 6 Sulphate and nitrate profiles in the sediment porewaters of Cores A and B.

both cores is very similar to the mean composition of other freshwater sediments (Bowen 1979; Hakanson and Jansson 1983).

3.2 DISTRIBUTION OF NICKEL AND ARSENIC IN LAKE SEDIMENTS

The vertical distributions of As and Ni below the mud-water interface and the areal distribution of the elements in the lakes sediments were examined using sediment cores collected during 1983 and 1985. McCulloch (1984) and Evans et al. (1984) reported Ni concentrations in 15 cores of Moira Lake sediments. In this study we measured the As concentration in 6 of these cores collected by McCulloch in 1983 (Fig. 2). The cores were selected so that the areal distributions of Ni and As could be compared. Two cores with high, intermediate or low Ni concentrations were chosen for these analyses.

Arsenic concentrations measured in the Moira Lake sediments were of similar magnitude to the Ni concentrations reported by Evans et al. (1986). Arsenic and Ni concentrations in this lake are much higher than those reported in most other systems (e.g. Hakanson and Jansson 1983; Nriagu 1983; NRC 1978). The vertical distribution of As in the sediment cores parallels that of Ni (Fig. 7). Both elements exhibit large changes in concentration throughout the core profile. Maximum concentrations, located between 10 and 20 cm below the mud-water interface, often exceeded 1000 ppm. The maximum concentrations were usually 5 to 20 times greater than values found near the surface or maximum depth of the core. We believe that the changes in concentration of Ni and As in the lake sediment cores reflect different inputs of the two elements to the lake during the past 150 years. However the history of milling and tailings management in the Moira River Basin is complex and leaching of contaminants from the tailings area is poorly quantified (Mudroch and Capobianco 1980). Milling activity in the basin increased after 1860 and reached a maximum during the mid-1900's. Between 1930 and 1958 refining activities declined and we hypothesize that discharges of Ni and As to the lake would follow changes in milling operations. The parallel changes in Ni and As concentrations (which occur despite significant differences in their geochemistry, see Section 3.3) support this hypothesis. In addition the concentration maximum is not correlated with significant changes in redox potential or in major anion or cation geochemistry. A correlation between the sediment geochemistry and concentrations of Ni or As would be expected if the concentration changes were caused by diagenesis in the cores.

Although parallel changes in Ni and As concentrations occur in the cores, the As concentration maximum is located nearer to the mud-water interface (Fig. 7). We interpret this difference to suggest that Ni inputs to the Moira River decreased earlier than did the inputs of As. However this hypothesis cannot be tested more rigorously until all cores are dated and the history of Ni and As inputs into the Moira River Basin has been documented in greater detail than is presently available.

The correlation between Ni and As concentrations observed within each core was also observed when the distribution of As and Ni between cores was compared. Cores with elevated concentrations of Ni also had elevated As concentrations. There was a strong correlation between the masses of As and Ni in the six cores studied (Fig. 8, $R=0.90$, $p<0.01$).

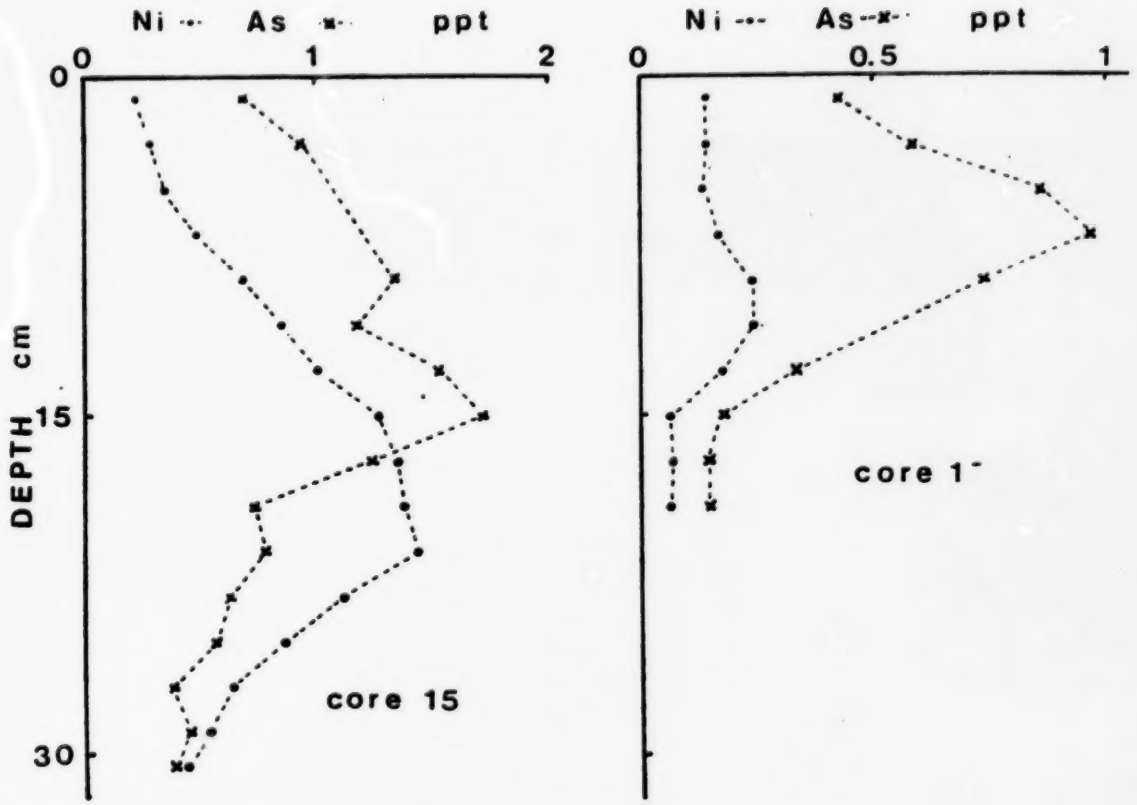

FIGURE 7 Distribution of total As and Ni in two cores of Moira Lake sediment.

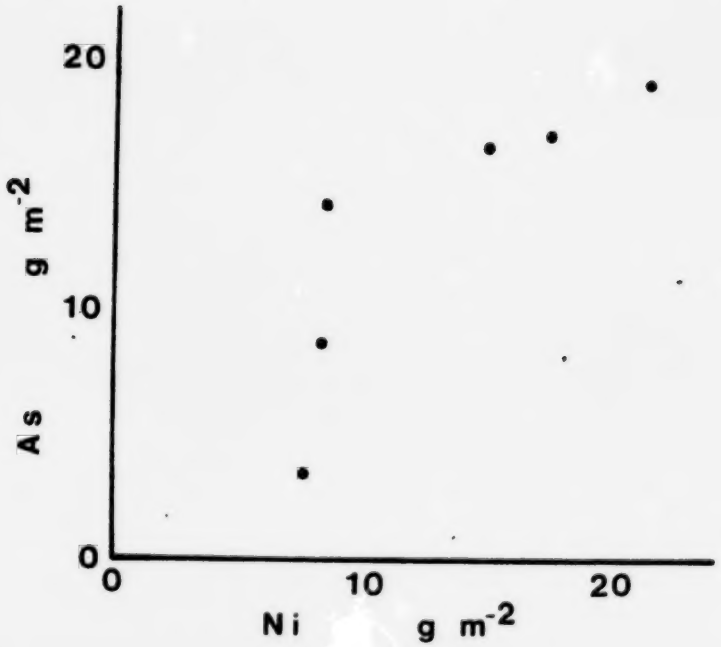

FIGURE 8 Correlation between Ni and As mass in Moira Lake sediment cores.

3.3 NICKEL AND ARSENIC IN MOIRA LAKE WATER

Samples of Moira Lake water were collected at the two coring sites (A and B) 1 metre above the lake sediments (Fig. 2). Since the lake was isothermal at the time of sampling, these samples are representative of the entire water column. No statistically significant difference was measured in Ni or As concentrations between the 2 sites and their results are pooled for the discussion below. Total As concentrations were ≈ 47 ppb and Ni measured 13 ppb (Table 3). The majority of both elements was found in the dissolved (< 0.40 μm) fraction. Only 2.1% of the Ni and 4.0% of the As were retained by the filtration. The distribution coefficients for Ni and As were 4×10^3 and 8×10^3 respectively. These values are lower than the majority of values reported by other studies (e.g. NRC 1978; 1981).

The As and Ni concentrations in both the lake sediments and the overlying water of Moira Lake were measured during this study. By pooling these results and correcting for the volume of lakewater and the mass of lake sediments, it is possible to compare the distribution of As and Ni in the entire lake system (Table 4). Both contaminants are found predominantly in the sediments. Concentrations in the bottom sediments are 10^4 to 10^5 times higher per gram dry weight than concentrations in the overlying water. The sediments contain > 97% of the total mass of As and 99% of the total mass of Ni present in the sediment-water system. Clearly the sediments comprise a significant reservoir of contaminants and the behaviour of Ni and As in Moira Lake will be largely determined by the elements' behaviour in the bottom sediments.

3.4 PARTITIONING OF NICKEL AND ARSENIC IN MOIRA LAKE SEDIMENTS

The distributions of Ni and As in different sediment fractions were determined by separating the porewater from the solid matrix and then sequentially extracting Ni and As from the matrix material.

The porewater concentrations of Ni and As and the vertical distribution of the elements at the 2 sites were very similar (Fig. 9). Arsenic concentrations in the porewater (Fig. 9) mimicked the distribution of the element in the matrix (see section 3.2). A subsurface peak in concentration of ≈ 1 ppm was significantly higher than concentrations measured near the mud-water interface or the maximum depth of the core. The As in the porewater was < 1% of the combined As on the matrix and in the porewaters. Porewater Ni concentrations were highest at the mud-water interface and decreased with depth to the maximum depth of the core (Fig. 9). Nickel concentrations in the porewater appeared to be completely independent of the Ni concentration on the solid matrix. The subsurface maximum in total Ni concentrations in the sediments was not mirrored in the porewater. These observations suggest that Ni was much less soluble in the deeper sections of the cores.

Nickel and arsenic were extracted sequentially from the sediment matrix using the procedure developed by Tessier et al. (1979). Cores collected at both site A and site B show very similar patterns of elemental distribution (Table 5, Appendix 2 and 3). Therefore the general trends in the results are examined below. The terminology used to describe each fraction is defined in section 2.3.

TABLE 3

NICKEL AND ARSENIC CONCENTRATIONS IN MOIRA LAKE WATER

	As	Ni
Dissolved	45.1±2.8 $\mu g.L^{-1}$	12.5±2.7 $\mu g.L^{-1}$
Particulate[1]	1.9±.26 $\mu g.L^{-1}$	0.27±.18 $\mu g.L^{-1}$
Particulate[2]	93 $\mu g.g^{-1}$	13 $\mu g.g^{-1}$
Distribution coefficient[2]	2067 $L.kg^{-1}$	1056 $L.kg^{-1}$

[1] particulate material retained by a 0.4 μm filter

[2] expressed per gram dry weight. The concentration of particulate material was 20.5 ± 4.3 $mg.L^{-1}$

TABLE 4

DISTRIBUTION OF NICKEL AND ARSENIC IN THE MOIRA LAKE SYSTEM

Element	Sediments[1]	Water
Ni	510×10^5 g	4.6×10^5 g
As	570×10^5 g	17×10^5 g

[1] calculation assumes sediment containing As and Ni only accumulates over 50% of the lake bottom and that concentrations of both elements deeper than 25 cm are not significant

The first extraction removes Ni that can be exchanged during a magnesium chloride wash. Very little Ni was found in this fraction (Fig. 10) and the amount of exchangeable Ni decreased significantly deeper in the cores. At the bottom of the cores the amount of exchangeable Ni was below the detection limit for the analyses. The second extraction removed Ni bound to carbonates. This fraction comprised 30 to 40% of the total Ni in the top 4 cm of the cores. Nickel in the carbonate extract decreased significantly in deeper sections (Fig. 10). Throughout the cores, 30 to 40% of the Ni was extracted from the iron and manganese oxide fraction. The relative amount of Ni in this fraction changed very little from the mud-water interface to the bottom of the cores. However the absolute concentrations were significantly higher near the subsurface total Ni concentration maximum (see Section 3.2). Pooling the data from all sections of the cores, the fraction containing the highest concentrations of Ni was the organic and sulphide fraction. On average, ≈ 50% of the total amount of Ni in the solid matrix was extracted with this treatment. However the average value disguises the fact that the relative importance of the organic fraction changes dramatically with depth in Core A (Fig. 10). In the top 4 cm < 20% of the Ni was found in the organic fraction. Deeper in the core this fraction contributes 50 to 70% of the total Ni present in these sections. While the carbonate and oxide fractions contain most of the Ni in sections close to the mud-water interface, organic bound Ni is clearly far more important below a depth of 10 cm (Fig. 10). The residual fraction of the matrix contained only a small amount of Ni to the total burden in Core A. Similar results were observed in the top half of Core B. However the bottom sections of Core B were composed of stones, gravel, sand and shells. This material was not deposited during the past 150 years and the small amounts of Ni found in the samples were likely deposited prior to the mining/milling operations at Deloro. More than 80% of the Ni measured in these sections was found in the residual extract (Appendix 3). This suggests that the Ni was located in the rock matrix and was transported to Moira Lake by erosional processes.

The concentrations of As were analyzed in the same extracts described in the previous paragraph. Since the chemistry of As and Ni is significantly different, it is not surprising that the distribution of the 2 elements in the various fractions is also different. A small fraction (1-10%) of the total As in the core was found in the exchangeable fraction (Fig. 11). The amount of As in the carbonate fraction ranged from 3 to 40%. Changes in the relative importance of this fraction do not correlate with the changes in the geochemistry of the core or with the distribution of Ni in the carbonate fraction. The majority of the As found in the cores was extracted by the manganese and iron oxide dissolution (Fig. 11). The organic fraction contained significantly lower concentrations of As (< 20%). Again the residual fraction was a small percentage of the total amount of As present in sediment Core A and in the top 10 cm of Core B. In the lower sections of Core B 30 to 76% of the As was measured in the residual extract (Appendix 2). This suggests that both As and Ni, located in the rock matrix were transported by erosional processes into Moira Lake.

Throughout Cores A and B more As than Ni was found in the exchangeable fractions. The oxide fraction also contained significantly more As than Ni. The relative distribution of both Ni and As in the different fractions changes significantly over the length of the cores. Although the interpretation of cores from site B is compounded by significant changes in the chemistry of the

solid matrix, the matrix in the cores collected at site A was relatively constant in all sections (Fig. 3, Appendix 5). Only the Ca and S^{-2} concentrations showed systematic changes over the length of the cores. These changes appear to correlate with changes in the distribution of Ni in the carbonate and organic/sulphide fractions. However more detailed geochemical modelling will be required to establish cause-effect relations. The changes in the proportions of Ni and As in different fractions suggests that there is a significant amount of diagenesis occurring in the cores. As a result of changes in the redox conditions in the core and other chemical and physical changes (e.g. Eh or compaction), the distribution of Ni and As among the various chemical fractions changes as the material is buried by newly deposited sediment.

TABLE 5

Average Chemical Speciation of As and Ni in Cores A and B

Fraction	As[2]		Ni[2]	
	Core		Core	
	A	B[1]	A	B[1]
Exchangeable	3	2	2	3
Carbonate	12	20	17	35
Oxide	64	62	37	37
Organic	10	9	42	19
Residual	10	7	3	3

[1] means for 0-12 cm interval

[2] values are expressed as a percentage of the total in the core

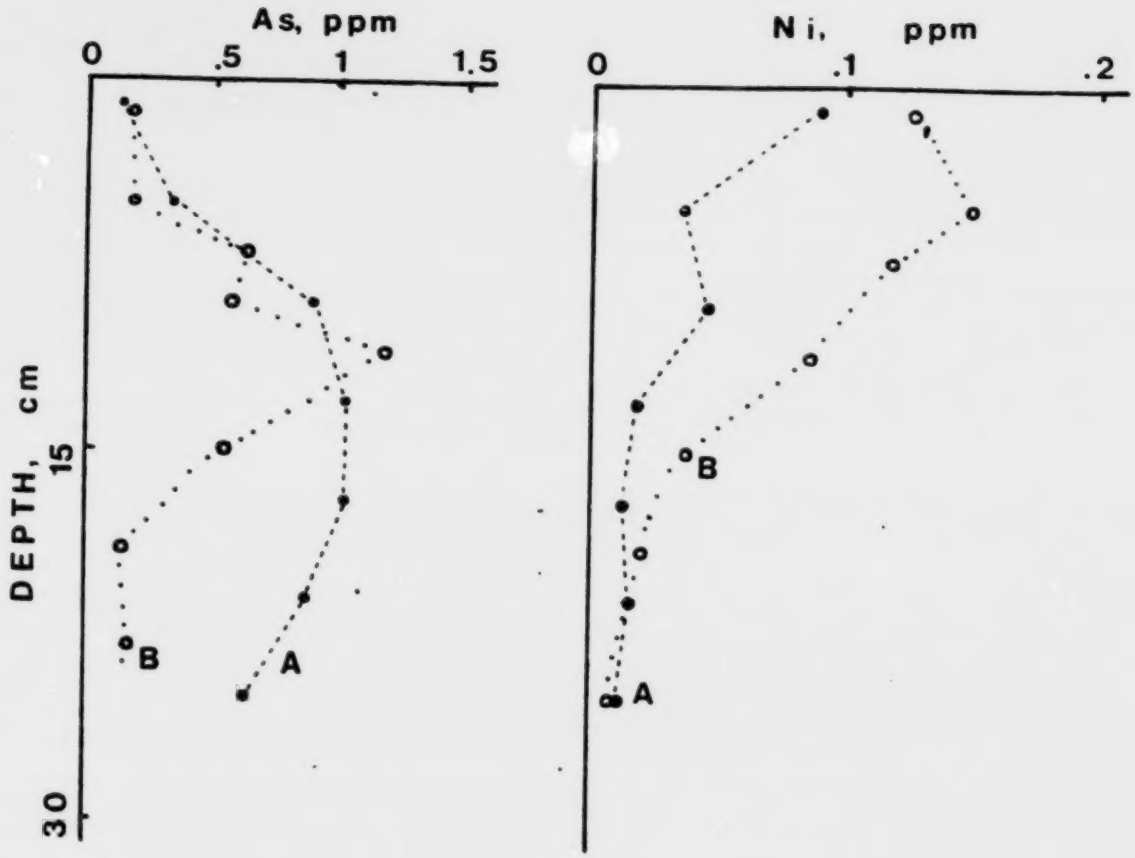

FIGURE 9 Ni and As concentrations in the sediment porewaters of Cores A and B.

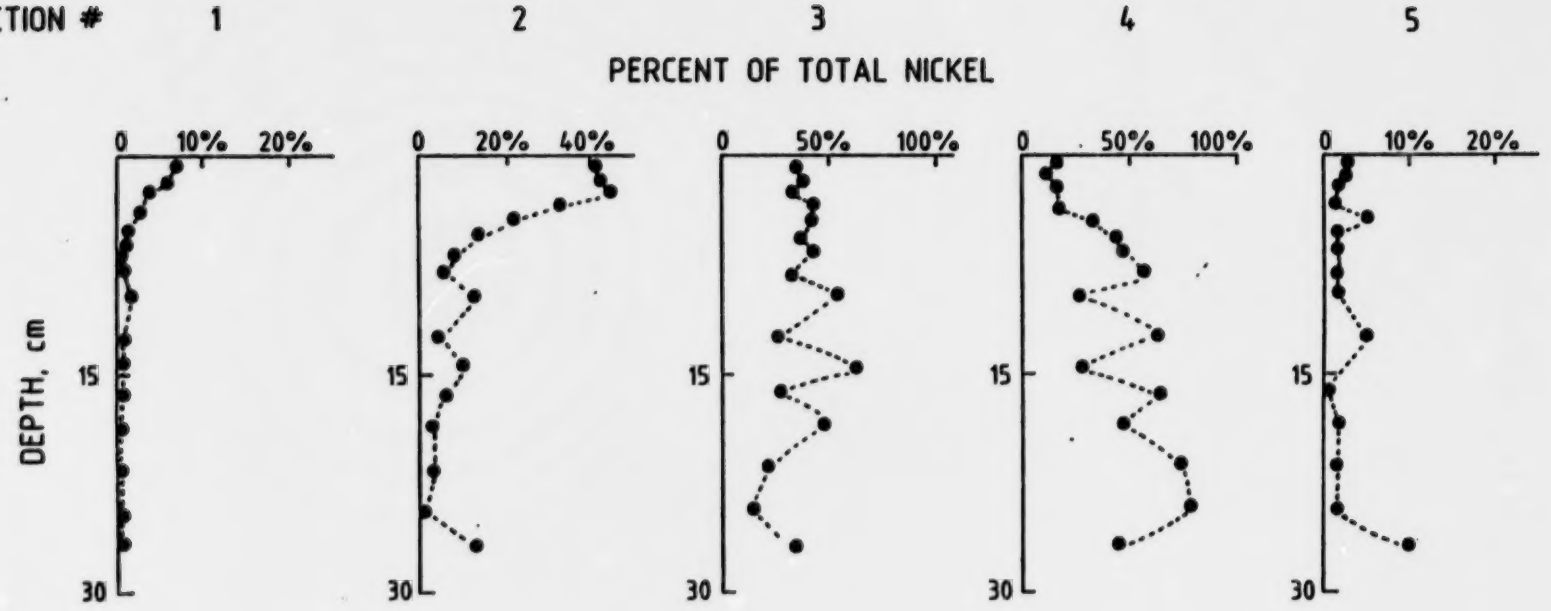

FIGURE 10. Chemical speciation of Ni in Moira Lake Core A.

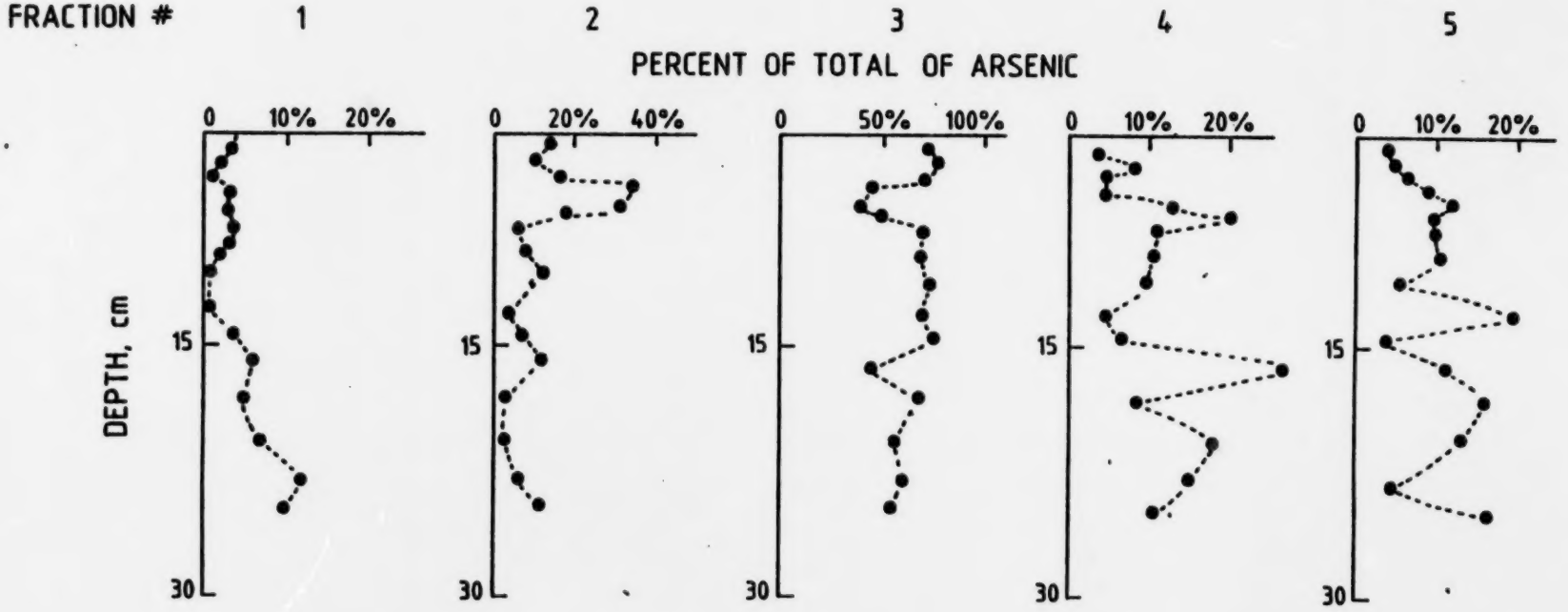

FIGURE 11. Chemical speciation of As in Moira Lake sediment Core A.

4.0 DISCUSSION

Arsenic and Ni have been input into Moira Lake from mining operations in the Moira River Basin during the past 125 years. Although we do not have historical information or measurements of the input for much of this time period, the results of this study suggest that the input of As and Ni is in a dissolved form. Concentrations of both elements measured in Moira Lake surface waters showed that the majority of the contaminants were present in a dissolved form. Although it could be argued that a significant fraction of the Ni and As inputs was attached to particulate material that was rapidly sedimented, this latter hypothesis can be rejected since Evans et al. (1986) did not find elevated sediment concentrations of Ni near the Moira River inflow. Additional support for the hypothesis that the inputs of the contaminants occurs in the dissolved phase, is found by the analyses of metal concentrations in the various sediment extracts. Since the residual mineralogic fraction contained small amounts of Ni and As, particulate inputs from the tailings must be small.

A very large fraction of the total amount of Ni and As in the Moira Lake system is found in the lake sediments. The lakewaters contain only a few percent of the total mass of contaminants. However this observation does not necessarily imply that all of the inputs of Ni and As is removed from the lakewater to the lake sediments. While data to determine the percentage of the input deposited in the sediments is available (MOE, unpublished data), the mass balances of Ni and As in Moira Lake have not been analyzed to our knowledge. Other studies on Lake Washington (Crecelius 1975), Lake Michigan (Klein 1975), and lakes in the Sudbury area (Nriagu 1983) all suggest that the retention of As in lake sediments is quite variable; from 55 to ≈ 100% of the input. Similar results have also been observed for Ni (Nriagu et al. 1982). Based upon these studies and those of Cornett and Ophel (1986) and Cornett et al. (1984), we expect that the fraction of the contaminant inputs retained in Moira Lake will be influenced by the water renewal time of the lake and by the lake's chemistry. Since Moira Lake flushes very rapidly during the spring and fall periods, much of the As or Ni inputs into the lake system may flow through the outlet. The exact fraction of these elements that is retained in the sediments will depend upon the rate the elements are removed to the sediments.

The historical or depth distributions of As and Ni in the Moira Lake sediment cores differ significantly from the majority of sediments studied to date (e.g. Dillon and Smith 1982; Evans and Rigler 1980; Kemp and Thomas 1976). In Moira Lake, sediment concentrations of Ni and As reach a subsurface maximum ≈ 10 to 18 cm below the mud-water interface. In other lakes the maximum concentrations of contaminants are usually found at or near the mud-water interface (e.g. Nriagu 1983; Carignan and Nriagu 1985). The different distribution of contaminants in Moira Lake sediments is hypothesized to be caused by significantly higher inputs (≈ 5 to 20x) 20 to 50 years earlier (Evans et al. 1986). In the sectioned cores there is not a 1:1 correlation between the Ni and As concentrations. However the concentrations of the two elements are very similar and As concentrations are usually higher nearer to the mud-water interface. The areal distribution of Ni and As in the lake bottom sediments is also strongly correlated and the average metal burden of As (13.8 g m^{-2}) is very similar to that for Ni (12.3 g m^{-2}). These observations lend further support to the arguments of Cornett and Ophel (1986), Evans et al. (1986) and Cornett et al. (1984) that the behaviour of different elements within a single lake is often very similar because the rate limiting processes such as settling velocity

of particles through the water column and diffusion of contaminants into the sediment matrix are the same for different elements.

Nickel and As in the sediments were separated into a porewater and matrix component. As observed in other studies (Carignan and Nriagu 1985; Mudroch and Capobianco 1980; NRC 1981; 1978) concentrations of Ni and As in the porewaters comprise a small fraction of the total amount of metal present in the sediments. However this small fraction may be important. The transfer of Ni and As from the water to the sediments and within the sediment column will be determined by the gradients in porewater concentrations. Concentrations of Ni were maximum near the mud-water interface and decreased deeper in the core. This measure is consistent with the hypothesis of Carignan and Nriagu (1985) that Ni is precipitated from the porewater in sulphide minerals under strongly reducing conditions. Arsenic also appears to be potentially mobile in the porewater. However the maximum concentrations of As in the porewater were located ≈ 15 cm below the mud-water interface. As a result As may be diffusing down a concentration gradient from the sediments into the overlying water. The significance of these transfers requires further investigation. Since these processes are important for other metals in other lakes (Carignan and Nriagu 1985; Santschi et al. 1986) it is easy to hypothesize that they may be significant in the transport of Ni and As in Moira Lake.

The distribution of Ni and As in the solid sediment matrix was fractionated using the sequential extraction procedure of Tessier et al. (1979). The majority of the As in the Moira Lake sediments was found in the iron and manganese oxide fraction. This observation, consistent with earlier studies of Crecelius (1975), Aggett and O'Brien (1985), and Aggett and Roberts (1986), is consistent with the hypothesis that As is incorporated into the sediments by co-precipitation with iron at the time of formation of hydrous oxides (Aggett and Roberts, 1986). In contrast to the distribution of As, most of the Ni was found in the organic fraction. Since this fraction also extracts metal sulphides (Tessier et al. 1979) this observation and the porewater gradients reported in section 3.4 are consistent with the hypothesis that Ni is precipitated from the sediments as an insoluble sulphide mineral (Carignan and Nriagu 1985). The fraction of Ni and As in the exchangeable extracts was very small when compared to the pool of metal in the other fractions. Although this could be interpreted as evidence that the exchange of the two metals between the sediments and overlying water is insignificant, we have insufficient data about the kinetics of Ni or As in the exchangeable fraction to support that conclusion. Similarly the relatively large quantities of Ni and As in the oxide fractions could lead to significant remobilization into the overlying Moira Lake waters if sediments at the mud-water interface became anoxic. Once again, there is too little information about the kinetics of oxide dissolution and transport in the sediment column to rigorously test this hypothesis. Rate constants for the transfer of As and Ni between the various fractions in Moira Lake sediments are needed before the final fate of the Ni and As currently found in Moira Lake sediments can be determined.

5.0 CONCLUSIONS AND RECOMMENDATIONS

This study has determined the distribution of Ni and As in the Moira Lake system. Results of these measurements show:

a) Ni and As leached from mine tailings located on the Moira River are accumulating in the lake sediments.

b) The concentrations of Ni and As in the lake water are very small relative to those in the bottom sediments.

c) The distributions of Ni and As in the bottom sediments are strongly correlated both in vertical concentration profiles from individual cores and in areal distribution in the bottom sediments.

d) Historical inputs of both Ni and As were 5 to 10 times higher than present day inputs during the period 20 to 50 years ago.

e) There are significant Ni and As gradients in the porewater that suggest that these elements are mobile in the sediment column.

f) Relatively large concentrations of both Ni and As are bound to iron and manganese oxides, or to carbonates and other easily exchangeable compounds. The Ni and As in these fractions could be remobilized from the sediments if the Eh decreased, ionic strength of the lakewater increased, or if the lakewater pH decreased.

g) This study focussed upon defining the distribution of Ni and As in the Moira Lake system. Future studies should examine: 1) the input/output budget of Ni and As in Moira Lake, 2) the rates that Ni and As are transported in the porewater column of the sediments, and 3) the kinetics of Ni and As transfer between the different chemical fractions in the bottom sediments. The definition of these rate constants coupled with the distribution data measured for this study, should provide the National Uranium Tailings Program with a strong data base from which to model the future behaviour of Ni and As in surface waters located downgradient from mine tailings.

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APPENDIX 1

ARSENIC AND NICKEL IN MOIRA LAKE SEDIMENTS

Six cores from Moira Lake were analyzed for total nickel and arsenic. These cores were collected between October 17 and November 14, 1983 by McCulloch (1984). The nickel in the cores was extracted and measured by McCulloch (1984). The arsenic was extracted and measured during this study (see Sections 2.3, 2.4). Values are expressed per gram dry weight.

CORE	SECTION (CM)	DRY MASS SECTION (G)	% WATER	NICKEL (UG/G)	ARSENIC (UG/G)
M2	0-2	1.16	97.70	283.50	709.61
	2-4	2.04	96.40	297.70	790.08
	4-6	2.77	95.70	428.30	952.39
	6-8	3.15	94.80	793.50	1213.43
	8-10	3.78	94.20	926.30	1317.77
	10-12	3.98	93.60	1272.20	1457.80
	12-14	4.56	92.90	1967.50	1462.38
	14-16	4.66	92.40	2293.30	1646.42
	16-18	4.60	92.60	2793.30	1373.57
	18-20	4.56	92.80	1360.70	855.58
	20-22	4.86	92.70	730.60	720.45
	22-24	4.68	92.37	584.20	538.23
	24-25	2.81	92.15	408.20	789.40
M8	0-2	.67	N/A	184.04	867.90
	2-4	.95		168.26	814.85
	4-6	1.26		218.69	1034.89
	6-8	1.62		252.50	1196.96
	8-10	1.86		418.00	1365.89
	10-12	2.46		435.80	1304.88
	12-14	3.01		467.75	1251.82
	14-16	3.58		544.63	1355.25
	16-18	3.86		719.10	1089.69
	18-20	4.18		1070.02	1693.00
	20-22	4.85		1454.40	1459.88
	22-24	5.14		1044.00	1004.70
	24-24.5	2.34		93.97	1017.80
M10	0-2	1.03	N/A	145.35	426.26
	2-4	1.39		139.17	589.43
	4-6	1.43		129.48	854.43
	6-8	1.56		168.46	966.50
	8-10	3.65		246.73	736.90
	10-12	8.12		242.29	246.10
	12-14	7.91		174.63	336.98
	14-16	23.32		62.90	181.72
	16-18	27.86		68.30	143.30
	18-19.5	36.24		62.50	143.89

CORE	SECTION (CM)	DRY MASS SECTION (G)	% WATER	NICKEL (UG/G)	ARSENIC (UG/G)
M11	0-2	.76	98.50	258.40	690.36
	2-4	1.03	98.10	271.80	1028.81
	4-6	1.45	97.60	341.90	1490.40
	6-8	1.68	97.30	409.30	1587.55
	8-10	2.30	96.30	726.00	1394.20
	10-12	3.51	94.50	1111.00	1235.20
	12-14	4.14	93.60	1042.90	1008.15
	14-16	4.27	93.50	1092.20	403.78
	16-18	4.46	93.10	895.70	386.97
	18-20	4.51	92.80	757.50	373.43
	20-22	5.25	92.20	637.80	317.12
	22-24	2.02	91.30	233.80	404.71
M13	0-2	.79	98.90	167.00	1071.30
	2-4	1.03	98.30	187.80	1344.70
	4-6	1.56	97.50	262.50	1389.88
	6-8	1.81	97.10	347.10	1598.34
	8-10	2.12	96.40	427.90	1440.80
	10-12	2.80	95.70	504.90	1102.80
	12-14	3.57	94.20	739.60	1134.01
	14-16	4.03	93.70	708.70	1194.30
	16-18	4.06	93.40	910.70	1246.58
	18-20	4.40	93.10	1045.10	991.57
	20-22	4.66	92.60	1296.00	1376.59
	22-24	4.87	92.60	1443.50	870.50
	24-26	5.10	92.00	1493.80	685.50
	26-28	5.38	91.70	1623.10	785.30
	28-30	5.37	91.50	1662.00	630.70
	30-32	6.22	90.80	1184.00	718.29
	32-34	6.23	90.20	747.60	388.35
M15	0-2	.85	N/A	228.60	699.30
	2-4	1.40		281.00	949.39
	4-6	1.98		350.80	N/A
	6-8	2.15		491.60	N/A
	8-10	3.15		693.10	1341.03
	10-12	3.98		852.50	1178.80
	12-14	3.96		1008.00	1515.29
	14-16	4.11		1263.00	1718.39
	16-18	5.25		1348.00	1120.00
	18-20	4.73		1371.00	732.87
	20-22	5.14		1438.00	789.72
	22-24	5.01		1113.00	624.13
	24-26	5.13		866.20	559.00
	26-28	5.34		625.10	377.18
	28-30	5.73		517.30	447.79
	30-30.5	3.09		421.60	389.12

APPENDIX 2

SPECIATION OF ARSENIC IN MOIRA LAKE SEDIMENT CORES

Two cores (A & B) of Moira Lake sediment were collected in November 1985 and sectioned into 1 cm slices under anoxic conditions. The arsenic was extracted sequentially under a nitrogen environment using the method of Tessier et al. (1979) (see Section 2.3). The extracted fractions were measured for arsenic using a hydride-generation method and flameless AA (see Section 2.4). Values are expressed per gram wet weight.

* indicates that the sample was lost and the reported values were estimated as the mean concentration of adjacent slices

CORE A

SECTION (CM)	FRACTION#1 EXCHANGEABLE	#2 CARBONATE	#3 FE/MN	#4 ORGANIC	#5 RESIDUAL	TOTAL (1 TO 5)
			UG/G ARSENIC			
0-1	2.15	12.76	55.34	3.29	2.86	76.40
1-2	.95	6.47	46.08	4.83	2.86	61.19
2-3	1.04	12.83	49.57	3.25	4.38	71.06
3-4	1.44	15.82	21.61	2.15	4.23	45.24
4-5	2.19	22.00	27.22	8.87	8.30	68.58
5-6	2.42	11.69	32.41	12.34	6.48	65.34
6-7	3.15	6.86	79.53	12.81	11.98	114.32
8-9	1.80	8.77	82.72	13.20	12.85	119.34
10-11	1.56	12.17	79.45	10.61	7.08	110.88
12-13	1.25	5.05	89.92	6.07	25.74	128.03
14-15	2.35	5.04	45.36	4.41	2.18	59.35
16-17	3.40	7.02	26.92	15.93	6.88	60.15
18-19	3.70	2.54	48.74	6.97	11.95	73.89
22-23	3.19	1.34	24.55	8.10	5.93	43.09
24-25	2.71	1.60	13.26	3.33	1.03	21.93
26-27	1.36	1.45	7.12	1.44	2.10	13.46

	% OF TOTAL FRACTION#1	%OF TOTAL #2	%OF TOTAL #3	%OF TOTAL #4	% OF TOTAL #5
			% ARSENIC		
	3	17	72	4	4
	2	11	75	8	5
	1	18	70	5	6
	3	35	48	5	9
	3	32	40	13	12
	4	18	50	19	10
	3	6	70	11	10
	2	7	69	11	11
	1	11	72	10	6
	1	4	70	5	20
	4	8	76	7	4
	6	12	45	26	11
	5	3	66	9	16
	7	3	57	19	14
	12	7	60	15	5
	10	11	53	11	16
%OF TOTAL IN CORE	3	12	64	10	10

CORE B

SECTION (CM)	UG/G ARSENIC FRACTION#1 EXCHANGEABLE	#2 CARBONATE	#3 FE/MN	#4 ORGANIC	#5 RESIDUAL	TOTAL (1 TO 5)
0-1	1.15	5.60	57.58	12.24	1.57	78.14
2-3	.34	11.73	38.27	6.63	4.16	61.13
4-5	.82	5.15	24.59	5.33	2.74	38.63
5-6	1.33	12.13	49.38	9.45	2.8*	72.29
6-7	1.84	11.68	42.81	4.76	2.81	63.90
8-9	2.18	3.60	61.65	12.96	4.5*	80.39
9-10	.19	20.21	25.10	.17	6.01	51.69
10-11	.09	15.89	14.48	.56	8.95	39.97
11-12	.14	18.57	16.29	.78	9.30	45.08
14-15	.28	1.25	1.27	.23	9.55	12.58
16-17	.09	.71	.45	<.005	.59	1.84
18-19	.07	.54	.55	<.005	.67	1.83
20-21	.03	.03	.47	<.005	.82	1.35
22-23	<.005	.04	.31	<.005	.7*	.35
24-25	<.005	.04	.59	<.005	.64	1.27
25-26	<.005	.03	.45	<.005	.78	1.26

	%ARSENIC %OF TOTAL FRACTION#1	%OF TOTAL #2	%OF TOTAL #3	%OF TOTAL #4	%OF TOTAL #5
	1	7	74	16	2
	1	19	63	11	7
	2	13	64	14	7
	2	17	68	13	0
	3	18	67	7	4
	3	4	77	16	0
	<1	39	49	<1	12
	<1	40	36	1	22
	<1	41	36	2	21
	2	10	10	2	76
	5	39	24	<1	32
	4	30	30	<1	37
	2	2	35	<1	61
	<1	12	68	<1	0
	<1	3	46	<1	51
	<1	3	36	<1	62
%OF TOTAL IN CORE	2	20	62	9	7

APPENDIX 3

SPECIATION OF NICKEL IN MOIRA LAKE SEDIMENT CORES

Two cores (A & B) of Moira Lake sediment were collected in November 1985 and sectioned into 1 cm slices under anoxic conditions. The nickel was extracted sequentially using the method of Tessier et al. (1979) with modifications under a nitrogen environment and measured using Zeeman background corrected AA (see Section 2.4).

CORE A

SECTION (CM)	UG/G NICKEL FRACTION#1 EXCHANGEABLE	#2 CARBONATE	#3 FE/MN	#4 ORGANIC	#5 RESIDUAL	TOTAL (1 TO 5)
0-1	2.02	11.75	9.30	4.42	.96	28.45
1-2	1.76	12.44	10.63	4.16	.89	29.87
2-3	1.44	17.51	13.46	6.62	.93	39.96
3-4	1.05	13.29	17.13	7.34	.99	39.80
4-5	.61	9.58	18.38	14.59	2.15	45.31
5-6	.65	9.89	26.79	30.46	1.39	69.38
6-7	.36	8.16	44.41	51.01	2.20	106.14
8-9	1.33	9.78	56.33	94.40	2.65	164.49
10-11	1.63	13.79	57.44	29.79	2.18	104.83
12-13	.36	11.61	64.01	134.09	10.91	220.98
14-15	.26	11.72	71.13	29.23	1.47	113.81
16-17	<.05	13.04	66.56	148.87	3.15	231.62
18-19	<.05	4.45	60.33	64.97	2.32	132.07
22-23	<.05	2.36	14.88	45.03	1.19	63.46
24-25	<.05	1.08	6.75	26.70	.55	35.08
26-27	<.05	1.22	2.75	4.03	.87	8.87

	% NICKEL %OF TOTAL FRACTION#1	%OF TOTAL #2	%OF TOTAL #3	%OF TOTAL #4	%OF TOTAL #5
	7	41	33	16	3
	6	42	36	14	3
	4	44	34	17	2
	3	33	43	18	2
	1	21	41	32	5
	1	14	39	44	2
	<1	8	42	48	2
	1	6	34	57	2
	2	13	55	28	2
	<1	5	29	61	5
	<1	10	62	26	1
	<1	6	29	64	1
	<1	3	46	49	2
	<1	4	23	71	2
	<1	3	19	76	2
	<1	14	31	45	10
%OF TOTAL IN CORE	1	11	38	49	2

CORE 8

SECTION (CM)	FRACTION#1 EXCHANGEABLE	#2 CARBONATE	#3 FE/MN	#4 ORGANIC	#5 RESIDUAL	TOTAL (1 TO 5)
	UG/G NICKEL					
0-1	1.43	9.38	5.70	5.26	<.05	21.76
2-3	.32	9.40	9.71	7.08	<.05	26.50
4-5	.72	8.92	6.76	5.24	<.05	21.64
5-6	1.36	17.03	8.58	6.37	<.05	33.34
6-7	2.43	8.62	7.95	5.09	<.05	24.09
8-9	<.05	1.81	21.86	8.77	<.05	32.44
9-10	<.05	35.02	34.48	17.43	4.62	91.55
10-11	<.05	36.94	28.58	3.39	10.06	78.97
11-12	<.05	35.41	32.35	3.60	8.00	79.36
14-15	<.05	.17	.97	1.39	5.85	8.37
16-17	<.05	.08	.29	1.30	7.44	9.10
18-19	<.05	.14	.20	.75	7.66	8.76
20-21	<.05	.16	.10	.42	6.18	6.85
22-23	<.05	.09	.21	.60	6.2*	.90
24-25	<.05	.12	.14	.50	6.22	6.98
25-26	<.05	.36	.19	.62	10.53	11.69

	% OF TOTAL FRACTION#1	% OF TOTAL #2	% OF TOTAL #3	% OF TOTAL #4	% OF TOTAL #5
	% NICKEL				
	7	43	26	24	<1
	1	35	37	27	<1
	3	41	31	24	<1
	4	51	26	19	<1
	10	36	33	21	<1
	<1	6	67	27	<1
	<1	38	38	19	5
	<1	47	36	4	13
	<1	45	41	5	10
	<1	2	12	17	70
	<1	1	3	14	82
	<1	2	2	9	87
	<1	2	1	6	90
	<1	10	23	67	87
	<1	2	2	7	89
	<1	3	2	5	90
%OF TOTAL IN CORE	1	35	34	14	16

* sample lost; average of two adjacent values

APPENDIX 4

MAJOR CATIONS IN THE PORE WATER OF MOIRA LAKE SEDIMENT CORES A AND B

Two cores (A & B) were collected in November 1985 and kept under a nitrogen environment during sectioning into 1 cm slices, and extraction of pore water. The pore water fractions were analyzed for cations using inductively-coupled plasma emission (ICP).

MAJOR CATIONS IN MOIRA LAKE PORE WATER - (UG/ML) -

CORE	SECTION (CM)	CALCIUM	MAGNESIUM	SILICON	IRON	MANGANESE	BARIUM	ALUMINUM
A	0-1	39	5.3	4.0	<.18	<.07	.15	<5
	1-2	39	5.3	2.0	.94	<.07	.15	<5
	2-3	33	4.9	.9	.21	<.07	.13	<5
	4-5	38	5.1	.9	.51	.08	.14	<5
	6-7	34	4.5	.8	.78	.19	.13	<5
	7-8	37	4.8	3.0	.75	<.07	.13	<5
	9-10	33	4.0	1.0	.93	.18	.14	<5
	13-14	28	3.5	3.0	.48	.21	.13	<5
	15-16	31	3.7	3.0	.50	.23	.15	<5
	17-18	33	3.5	5.0	.63	.26	.15	<5
	19-20	31	3.6	3.0	1.02	.21	.14	<5
	21-22	35	4.0	1.8	.59	.28	.15	<5
	23-24	33	4.2	1.0	.94	.25	.13	<5
	25-26	31	3.9	.7	1.1	.26	.13	<5
	27-28	36	4.2	3.0	2.62	.31	.16	<5
B	0-1	53	5.9	6.0	3.4	.37	.21	<8
	1-2	67	7.2	3.0	4.2	.43	.27	<8
	3-4	72	7.4	4.0	2.0	<.11	.23	<8
	5-6	38	5.4	2.2	<.28	<.11	.13	<8
	7-8	35	4.6	2.3	.61	.13	.13	<8
	8-9	27	4.2	3.0	.80	.24	.10	<8
	9-10	74	5.3	4.0	4.4	.56	.21	<8
	10-11	47	4.7	10.0	1.1	.43	.13	<8
	13-14	35	3.8	10.0	1.2	.41	.14	<8
	14-15	21	2.1	9.0	1.1	.36	.09	<8
	15-16	22	2.4	11.0	.9	.27	.09	<8
	17-18	23	2.6	12.0	1.5	.35	.12	<8
	20-21	17	1.8	11.0	2.7	.16	.07	<8
	23-24	26	3.2	10.0	1.1	.20	.11	<8
	24-25	29	3.2	9.0	1.0	.36	.11	<8
AVERAGE	% ERROR	7.4%	8.6%	30%	5%	5%	8%	

APPENDIX 5

MAJOR CATIONS IN MOIRA LAKE SEDIMENT

Two sediment cores (A and B) from Moira Lake were collected in November 1985 and sectioned into 1 cm slices. The cations were measured in digested fractions of the sections by inductively-coupled plasma emission spectrophotometry. Values are expressed per gram dry weight.

MAJOR CATIONS IN MOIRA LAKE SEDIMENTS (UG/G)

CORE	SECTION (CM)	CALCIUM (*10^3)	MAGNESIUM (*10^3)	SILICON	IRON (*10^3)	MANGANESE	BARIUM (*10^3)	ALUMINUM (*10^3)
A	0-1	44	6.3		62		.46	51
	1-2	54	6.7		24		.45	21
	2-3	55	6.8		39		.43	27
	4-5	71	5.9		38		.43	22
	5-6	22	7.9		55		.53	38
	6-7	54	7.2		46		.53	31
	9-10	31	7.8		45		.57	35
	10-11	34	9.4		54		.66	41
	13-14	28	6.8		46		.66	38
	15-16	24	8.3		47		.65	43
	17-18	24	8.8		46		.61	43
	19-20	24	8.6		61		.61	43
	23-24	24	8.1		61		.62	44
	25-26	23	8.3		58		.64	43
	27-28	20	6.8		54		.54	38
B	1-2	70	6.7		33		.55	37
	3-4	66	5.4		31		.36	23
	5-6	66	5.8		39		.54	27
	7-8	54	6.4		37		.51	39
	8-9	34	6.8		33		.57	47
	9-10	33	7.0		33		.64	56
	11-12	18	6.7		29		.60	56
	13-14	14	7.0		35		.57	63
	15-16	11	6.5		33		.57	62
	17-18	15	7.6		39		.62	61
	19-20	15	7.5		35		.63	59
	20-21	23	9.5		45		.39	62
	21-22	15	5.8		30		.55	47
	23-24	41	2.9		15		.24	30
	25-26	16	7.1		34		.59	63
AVERAGE % ERROR		9%	10%		9.7%		9.5%	9.8%

APPENDIX 6

PORE WATER CHEMISTRY OF MOIRA LAKE SEDIMENTS

Two sediment cores (A & B) were collected from Moira Lake in November 1985. Subsequently the specific conductance (K), pH, Eh, S^{-2}, F^{-}, NO_3^{-} and SO_4^{-2} concentrations were measured using the methods described in Section 2.6

PORE WATER CHEMISTRY OF MOIRA LAKE SEDIMENTS

CORE	SECTION	K us/cm	pH	Eh mv	SULPHIDE ppb	FLUORIDE ppm	CHLORIDE ppm	NITRATE ppm	SULPHATE ppm
A	0-1	204	8.1	140	5	2.4	9.9	16.9	
	1-2	178	8.1	150		1.3	10.0	21.7	33.3
	2-3	153	7.9	160	5	.8	8.6		26.5
	3-4		7.8	129	7		9.5	21.8	35.1
	4-5	168	7.6	87	7	1.4	9.0		27.7
	5-6		7.9	70	35	1.4	7.8		23.6
	6-7	130	7.7	65	20	1.6	7.4	3.4	22.4
	7-8								
	8-9		8.0	28	50	2.6	8.2	4	20.4
	9-10	163							
	10-11		8.0	38	120	2.7	7.8		14.1
	11-12								
	12-13		7.9	15	20	3.2	8.5		8.3
	13-14	125	8.0						
	14-15		7.9	15	80	2.6	7.9		
	15-16	138							
	16-17		7.9	0	20	2.3	7.4	3.7	7.0
	17-18	168							
	18-19		8.0	0	30	1.8	6.8		4.3
	19-20	140							
	20-21								
	21-22	138							
	22-23		7.7	20	20	1.4			6.4
	23-24	125							
	24-25		8.0	12	50	1.4	7.9	2.4	<3.0
	25-26	112							
	26-27	140	8.0	0					
	27-28	138							
B	0-1	247	8.6	160	1	1.9	9.2	35.7	24.8
	1-2		8.7	130		2.4	9.9	44.0	26.1
	2-3	212	8.6		10	.9	9.7		28.1
	3-4	183	8.6	140					
	4-5	178	8.4	145	3	3.0	8.4		27.3
	5-6			115		.8	7.8	17.4	25.7
	6-7	168	8.9	130	1	2.4	10.6	8.6	36.3
	7-8	268	9.2	125	<.01	1.7	4.5		26.2
	8-9	282		135	2				
	9-10		8.6	130	.2	1.8	7.5	29.4	26.4
	10-11								
	11-12								
	12-13					3.6	10.0	27.9	28.2
	13-14				1				
	14-15	202	8.3	140	<.05	1.2	10.8		27.4
	15-16		9.1	120	<.05				
	16-17								
	17-18	314	8.9	130	2				
	18-19								
	19-20								
	20-21		8.7	140	.1	.7	10.2	35.2	
	21-22								
	22-23								
	23-24								
	24-25	228			.3				
	25-26		8.6	180					